BELLCOMM, INC.

955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 12077

SUBJECT: Electrical Effects of Partial Shadowing of the Skylab Workshop Solar Array - Case 620

DATE: December 30, 1970

FROM: W. W. Hough
J. J. Sakolosky

ABSTRACT

Selective shadowing of individual cells in the Skylab Workshop solar array can result in reverse voltages sufficient to cause Zener breakdown of the shadowed cells. However, analysis of several possible cases of array shadowing demonstrates that an unlikely combination of circumstances is required for reverse breakdown to occur. First, of 154 cells in a series string, only one must be in full or almost full shadow and the others must be fully illuminated. Because of the geometry of the array and the vehicle, such a shadow can arise only from the edge of the deployed meteoroid shield while the vehicle is rolled a specific amount, or from antennas mounted on the end of the ATM arrays. Second, the breakdown voltage of the shadowed cell must be less than the breakdown voltages of more than 90% of the cells tested.

Should Zener breakdown of an individual cell occur, it is not likely that measurable harm will be done. Of the small sample of these cells which have exibited breakdown at the low reverse voltages which are possible due to selective shadowing, two recovered completely. The third possessed characteristics of a low impedence resistor after breakdown and if it were in series with 153 other properly performing cells, it would not measurably affect the power output of the string.

MSFC has suggested that all solar cells be screened prior to installation and that those with low breakdown voltages not be used. If this is done, the array design should be completely acceptable from the standpoint of electrical effects of partial shadowing.

(NASA-CR-116258) ELECTRICAL EFFECTS OF PARTIAL SHADOWING OF THE SKYLAB WORKSHOP SOLAR ARRAY (Bellcomm, Inc.) 28 p

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MEMORANDUM FOR FILE

INTRODUCTION

The Skylab Workshop solar array will be wired without parallel connections between individual solar cells in the series strings. The string of single cells was adopted to eliminate the possibility of "hot-spot" cell failure under conditions of partial array shadowing. An excellent exposition of the hot-spot failure mode for solar arrays has been given by its discoverers, Blake and Hanson of General Electric, in Reference 1. Hot-spots occur in the illuminated portion of a partially shadowed element of several paralleled cells, and can cause solder or adhesive failures. The voltage across a shadowed element is driven into the reverse region to pass the current generated by other, unshadowed elements in the series string. The power that is dissipated in the illuminated portion of the element, where relatively high current can flow, is on the order of several watts for the parallel-cell schemes considered for Skylab.

When one to several cells of a single-cell series string are shadowed, reverse voltages will still develop across those elements. The shadowed cells will act as reverse biased diodes, but the current passed will be small unless the reverse voltage exceeds the Zener breakdown point. If Zener avalanche occurs, a shadowed element can dissipate substantial amounts of power. Resulting temperatures will be less than those due to partial shadowing of paralleled cells (hot-spot) because the power dissipated is less and the solar input is absent. However, a shadowed cell that experiences Zener avalanche might not recover when it is again illuminated. That is, it might not exhibit proper voltage - current (V-I) output characteristics.

The study reported here was performed to evaluate the susceptability of the Workshop solar array to Zener breakdown of shadowed cells.

WORKSHOP SOLAR ARRAY SHADOW GEOMETRY

The geometry of the Workshop Solar Array System (SAS) is shown in Figure 1. Each of the two wings contains 30 interchangeable panels which are further divided into four electrically independent modules. A module consists of four series strings of 154-2x4 cm cells which are connected in parallel only at the ends of the strings. Each string is geometrically folded in half to give a 77x8 cell laydown on each module. Electrically, the SAS is divided into eight separate power producing groups, and each group is connected to one of the Airlock Power Conditioning Groups consisting of a charger, battery, and regulator. Each SAS group consists of 30 modules, or 120 strings, in parallel.

In attitudes other than solar inertial,shadowing of the solar cells can occur from three sources. The first is the deployable beam-fairing, which can cast only a shadow whose edge is parallel to the strings of cells. (see Figure 1). The shadow on the affected half of a partially shadowed string will be uniform, and high reverse voltages across individual cells cannot build up. Zener breakdown will therefore not occur due to shadowing by the beam-fairing. The second source of shadowing is the Workshop forward and aft skirts and the meteoroid shield. The shadowing edge is perpendicular to the strings of cells. If one cell in a string is shadowed by these cylinders, generally two will be shadowed because of the geometrical fold in the center. The exception is that string where the shadow of the end of the deployed meteoroid shield falls between folded halves of the string. The third source of shadowing is the ATM solar arrays and devices mounted to the ends of these arrays. Shadows from this source can also cover cells in only one-half of a folded string.

To completely specify possible shadow patterns, the effects of the penumbra must be considered. The penumbra is the space of partial illumination between the umbra, or perfect shadow, and the fully illuminated space. It arises because the sun, as viewed from the earth, is not a point source. The illuminance at any point in the penumbra is determined by how much of the sun's disk can be seen from the point, modified by the limb darkening effect.

The geometry pertinent to the study of the penumbra is given in Figure 2. The angle subtended by the sun is called ξ and at earth distance has a value of .009305 radians. The width of the penumbra due to a shadowing straight edge on a surface perpendicular to the solar vector is

$$P = \xi L = .009305\ L \tag{1}$$

where L is the distance from the shadowing edge to the shadowed surface. At a distance X into the penumbra from the umbra, a segment of the sun's disk of rise A is visable above the shadowing edge. If R is the radius of the sun, we see that

$$\frac{A}{2R} = \frac{X}{P} \tag{2}$$

Limb darkening refers to the fact that the luminous intensity (luminance) is not constant over the sun's disk, but drops off as the distance from the center of the disk increases. If i_o is the luminance at the center of the disk as seen from the earth, a good approximation for the luminance at a distance r from the center is

$$i = i_o(1-u+u\ \cos\phi) \tag{3}$$

where $\phi = \sin^{-1}\frac{r}{R}$ (see Figure 2) and u determines the degree of limb darkening. If u = 0, the luminance is uniform; if u = 1, the luminance decreases to zero at the limb. Experimentally determined values for u indicate that it is a function of wavelength, but an average value of 0.6 is satisfactory for a first-order analysis of the effect.

To determine the illuminance at a distance X into the penumbra, we integrate the luminance over the segment of the sun's disk of rise A that can be seen from X. If the half-central angle is ψ, and B is the radial distance from the center of the sun's disk to the projected shadowing edge at the variable angle θ, the integral becomes

$$I = 2 \int_0^{\psi} \int_B^R i \; r \; dr \; d\theta \qquad (4)$$

The limit B is given by

$$B = \frac{R-A}{\cos\theta}$$

and the limit ψ by

$$\psi = \cos^{-1}\left(\frac{R-A}{R}\right)$$

so

$$I = 2i_o \int_0^{\psi} \int_{\frac{R-A}{\cos\theta}}^{R} \left\{1-u+u\,\frac{\sqrt{R^2-r^2}}{R}\right\} r \; dr \; d\theta \qquad (5)$$

This integral has been evaluated for A between zero and R with u = 0, .6, and 1, and the results are plotted in Figure 3 as a ratio of full-sun illuminance, I_o, which is just twice this integral evaluated at A = R. The symmetry of the problem about the center of the sun, and equation (2), permit the abscissa of Figure 3 to be labeled X/P and the variation in illuminance through the entire penumbra to be plotted.

In the case of shadowing of the Workshop arrays, the width of the possible penumbras are such that no cell in a string can be completely shadowed and all others be completely illuminated. Minimum possible penumbra widths from the two important sources of shadow, the meteoroid shield and the ATM arrays, can be determined with the aid of Figure 4. A spacecraft roll away from the solar inertial attitude by at least 22.42° is required for the Position II wing to be shadowed by the meteoroid shield. With this roll angle, the minimum distance from the shadowing edge to the array is 136.85 inches. The width of the penumbra perpendicular to the sun line is given by (1), but the actual penumbra on the array is wider because of the roll angle. That is

$$P_M = \xi\ L_M/\cos\theta_R = 1.38 \text{ in} = 3.5 \text{ cm}$$

The minimum width penumbra due to the ATM array shadow will occur on the Position IV solar array wing, which is 182 inches away. In this case, the array can be perpendicular to the sun line, and the minimum width of the penumbra comes directly from (1)

$$P_A = \xi\ L_A = 1.69 \text{ in} = 4.3 \text{ cm}$$

The minimum penumbra therefore occurs when the meteoroid shield shadows the array with a pure spacecraft roll out of the solar inertial attitude. Even with the effect of reduced illumination on the panel due to the roll angle cosine loss, this is the worse-case shadow.

Five percent of the two-centimeter width of each cell is covered by a solder strip, but this area is not lost because of the overlapped or shingled cell laydown. The effective exposed cell width is 1.9 cm. Therefore the minimum penumbra covers 1.84 cell widths or a cell width occupys 54.3% of the penumbra. Average illumination intensity on a cell in this worst-case penumbra may be determined from Figure 3 by integrating the appropriate portion of the illumination profile over the cell width and then dividing by the cell width. For example, the average illumination on a cell, one side of which is just at the transition to full sunlight and the other is 1.9 cm into the penumbra, is

$$I_{AVG} = \frac{1}{1.9} \int_{1.6}^{3.5} I(x)\,dx$$

For the normalized parameters of Figure 3:

$$\frac{I_{AVG}}{I_o} = \frac{1}{.543} \int_{.457}^{1.0} \frac{I(X/P)}{I_o} \, d(X/P)$$

The average cell illumination intensity was determined for the cases examined in this memorandum graphically from Figure 3.

ELECTRICAL CHARACTERISTICS OF SHADOWED STRINGS

A forward current-voltage (I-V) characteristic typical of illuminated solar cells in the SAS is shown in Figure 5. Figure 6 illustrates the resultant characteristic for a series string of 154 cells at 25°C. The operating point of an SAS electrical group is maintained in the vicinity of the peak power point by a peak power tracker. Since a group consists of 120 strings in parallel, it would normally be operating at a voltage of 72.4 volts, hereinafter referred to as V_B, and a current of 30.2 amperes (120 x .252 amps). The effect of illumination intensity on a single solar cell is shown in Figure 7. Short circuit current, I_{sc}, is a strong function of illumination, but the open circuit voltage, V_{oc}, is relatively unaffected. On the other hand, V_{oc} is a strong function of operating temperature while I_{sc} is relatively unaffected.

If one of the cells in a string becomes partially shadowed, a shift in the operating point of every other cell in the string will occur. The total voltage across the string, however, must remain constant at V_B, the operating voltage of the unaffected parallel strings. An appropriate equivalent circuit for the section, shown in Figure 8, consists of the partially-shadowed string in parallel with a battery of voltage V_B. V_U is the voltage across the unaffected (i.e., fully illuminated) cells in the string, and V_A is the voltage across the affected (partially shadowed) cells.

$$V_A + V_U = V_B, \text{ a constant} \tag{6}$$

When a cell becomes shadowed, its current generating capability decreases, causing the current through the string to decrease. The operating point of each illuminated cell must therefore shift in the direction of decreasing current as a common current is passed through each cell of the string. Accordingly, the voltage across each illuminated cell must increase, (see Figure 5) increasing V_U above its value in an unshadowed string. But the operating voltage of the group, V_B, is held constant. Therefore V_A, the voltage across the shadowed cells, must decrease. In fact, in the usual case V_A actually becomes negative and the shadowed cells become reverse biased. The new operating point of the string may be determined by a graphical solution of equation (6). The intersection of the reverse V-I characteristic for the partially shadowed cell with the V-I characteristic for the voltage difference, $V_B-V_U=V_A$, gives the common current solution.

Piecewise linear approximations of the reverse characteristics for the solar cells in the SAS were obtained from Reference 2 and are shown in Figure 9. Figure 10 illustrates the current characteristic for 153 fully illuminated cells in the string as a function of V_B-V_U. V_B is taken as the operating voltage at the peak power point and is a constant.

The operating points for five cases of partial shadowing of an individual string by the meteoroid shield were determined. A 22.42° roll of the vehicle from solar inertial is required for this to occur and the resulting cosine loss in current output has been accounted for in all cases.

CASE 1: The first case considered is when the penumbra from the edge of the meteoroid shield covers one first row cell of a string. The illumination of the cell is decreased to 76% of full intensity. The operating point of the string is determined by the intersection of V_A with V_B-V_U in Figure 11. Depending on the leakage characteristics of the cell, the new string operating current is between 205 ma and 220 ma. The reverse voltage across the partially shadowed cell will range from 4 to 7 volts.

CASE 2: The penumbra from the edge of the meteoroid shield has now advanced to include two consecutive cells in the string. The relative illumination intensities are .76 (cell in 2nd row) and .17 (cell in first row) of full illumination. The reverse characteristic for the less illuminated cell intersects with V_B-V_U in Figure 12 over a current range of 57 to 117 ma. Since the short circuit current of the cell at 76% of full illumination is 200 ma, this cell will not become reversed biased. The reverse voltage across the highly shadowed cell ranges between 14.5 and 16.5 volts.

CASE 3: In this case the shadow cast by the edge of the meteoroid shield has advanced still further to include three consecutive cells in a string. The cell nearest the SIVB tank is in complete shadow and the next two cells outward are within the penumbra. The relative illumination intensities are 0%, 17%, and 76%. Notice in this case that, depending on cell leakage characteristics, the string operating current (Figure 13) could exceed 45 ma, the short circuit current of the cell at 17% of full illumination. If this happens, then both cells will become reverse biased, and the voltage, V_A, will occur across the series combination.

CASE 4: For this case the penumbra from the SIVB tank or meteoroid shield is assumed to just include the first row of cells of a given module. Because each string doubles back on itself, two cells of each string will be in the penumbra. The illumination of each cell in the row is decreased to 76% of full intensity. Assuming the two cells to have identical reverse characteristics, the new operating point of the string is determined in Figure 14. By the assumption, the voltage, V_A, divides equally across each of the partially shadowed cells.

CASE 5: In this final case, the shadow cast by the SIVB tank has advanced to include the first two rows of cells along the wing. Each string now has two cells at an illumination level of .76 and two cells at an illumination level of .17. As we saw earlier, the current through the highly shadowed cell will determine the new operating point; the cell at .76 of full illumination intensity does not become reverse biased. The new operating point is determined in Figure 15.

Table I lists the string operating current, reverse voltage across the shadowed cells, and power dissipated in the shadowed cells for each of the five cases examined. Maximum power dissipation of approximately 1.7 watts occurs in the second case, and this is not excessive. The maximum reverse voltage across a single cell, 17.2 volts, occurs for the completely shadowed low leakage cell in the third case. In general, the reverse voltage across the shadowed cell increases with the degree of shadowing; reverse voltage decreases as cell leakage increases.

TABLE I: OPERATING POINT PARAMETERS FOR THE FIVE CASES EXAMINED

Case	Cell Leakage	String Current	Reverse Voltage per cell	Power Dissipated per cell
1	High	222 ma	4.2 volts	0.93 watts
	Low	207 ma	7.0 volts	1.45 watts
2	High	118 ma	14.7 volts	1.73 watts
	Low	58 ma	16.4 volts	0.95 watts
3	High	79 ma	16.0 volts	1.26 watts
	Low	14 ma	17.2 volts	0.24 watts
4	High	214 ma	2.9 volts	0.62 watts
	Low	203 ma	3.7 volts	0.74 watts
5	High	84 ma	8.0 volts	0.67 watts
	Low	52 ma	8.3 volts	0.43 watts

The Zener breakdown voltage of the solar cells discussed in Reference 2 (and used with Figure 9) varies between 23 volts and 32 volts. Data from more recent tests on a larger sample indicate that a small percentage of the cells ($\sim$10%) may break down at reverse voltages less than 20 volts if their temperature is high (>25°C). When a group is operating at its peak power point, the maximum voltage difference V_B-V_U is between 17 and 18 volts (open circuit condition in affected string). Under these conditions it is unlikely that the reverse breakdown voltage of a shadowed cell will be exceeded. If some error exists between the peak power point and the actual operating point, the magnitude of the reverse voltage may increase. The performance specification for the peak power tracker allows a 5% deviation (in power) from the actual peak power point. (Reference 4). Error may occur on both sides of the actual peak power point. A 5% error in power could give rise to a 3.5 volt decrease in the group operating point, which could in turn increase the open circuit difference between V_B-V_U to 21.5 volts.

Although Zener breakdown of SAS solar cells under conditions of partial shadowing is possible, a very unlikely combination of circumstances is required. First, full or almost-full shadow must cover only one of the 154 cells in a string, and because of the center fold in each string, only the edges of the deployed meteoroid shield and antennas at the tip of the ATM arrays can cause these shadows. Second, the particular cell in such a shadow must have a very low Zener breakdown voltage. Third, the array must be operating close to maximum power; if it is not, the operating point will be on the high voltage-low current side of the peak power point, decreasing V_B-V_U and the likelihood of breakdown. Fourth, likelihood of breakdown is enhanced at peak power output only if allowable error by the peak power tracker is on the low-voltage side.

An array temperature of 25°C has been used for most of the preceeding discussion. Array temperature variation over the sunlit portion of the orbit causes variations in the cell reverse breakdown voltage and in the voltage V_B-V_U. Unfortunately, data concerning these variations are scarce, particularly with regard to cell reverse breakdown. Recent test data indicate that reverse breakdown voltage of the solar cells varies inversely with temperature (Reference 3). The change in V_B-V_U is also an inverse relationship with temperature (Reference 5). Thus the critical voltages both change in the same direction as a function of temperature, and it is unlikely that temperature variations will affect the above conclusion, which is that Zener breakdown in partially-shadowed strings of cells in the Workshop solar array is very unlikely.

Let us now consider what the consequences of breakdown might be should the unlikely occur. In the same recent tests in which a few (3 of 35) cells with low breakdown voltages were found, two-thirds (2) of the cells which did breakdown recovered (Reference 3). That is, they retained the same V-I characteristics that they possessed prior to breakdown. The one-third (1) that didn't recover possessed, after breakdown, a characteristic similar to that of a low-impedence resistor. Such a failure is of little consequence if the failed cell is in series with 153 good ones - it does not cause failure of the entire string.

CONCLUSIONS

The fact that Zener breakdown in unlikely, and the fact that if it does occur it probably won't do any measurable harm leads to the final conclusion that the present series string design of the SAS is acceptable from the standpoint of the electrical effects of partial array shadowing. MSFC has recommended that the cells used in the SAS be screened to eliminate those with low reverse breakdown voltages before installation. This step, it appears, assures an acceptable design.

ACKNOWLEDGEMENT

J. L. Miller of the Astrionics Laboratory at MSFC supplied data on cell characteristics and offered other helpful advice. His cooperation is appreciated.

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Attachments
References
Figures 1-15

REFERENCES

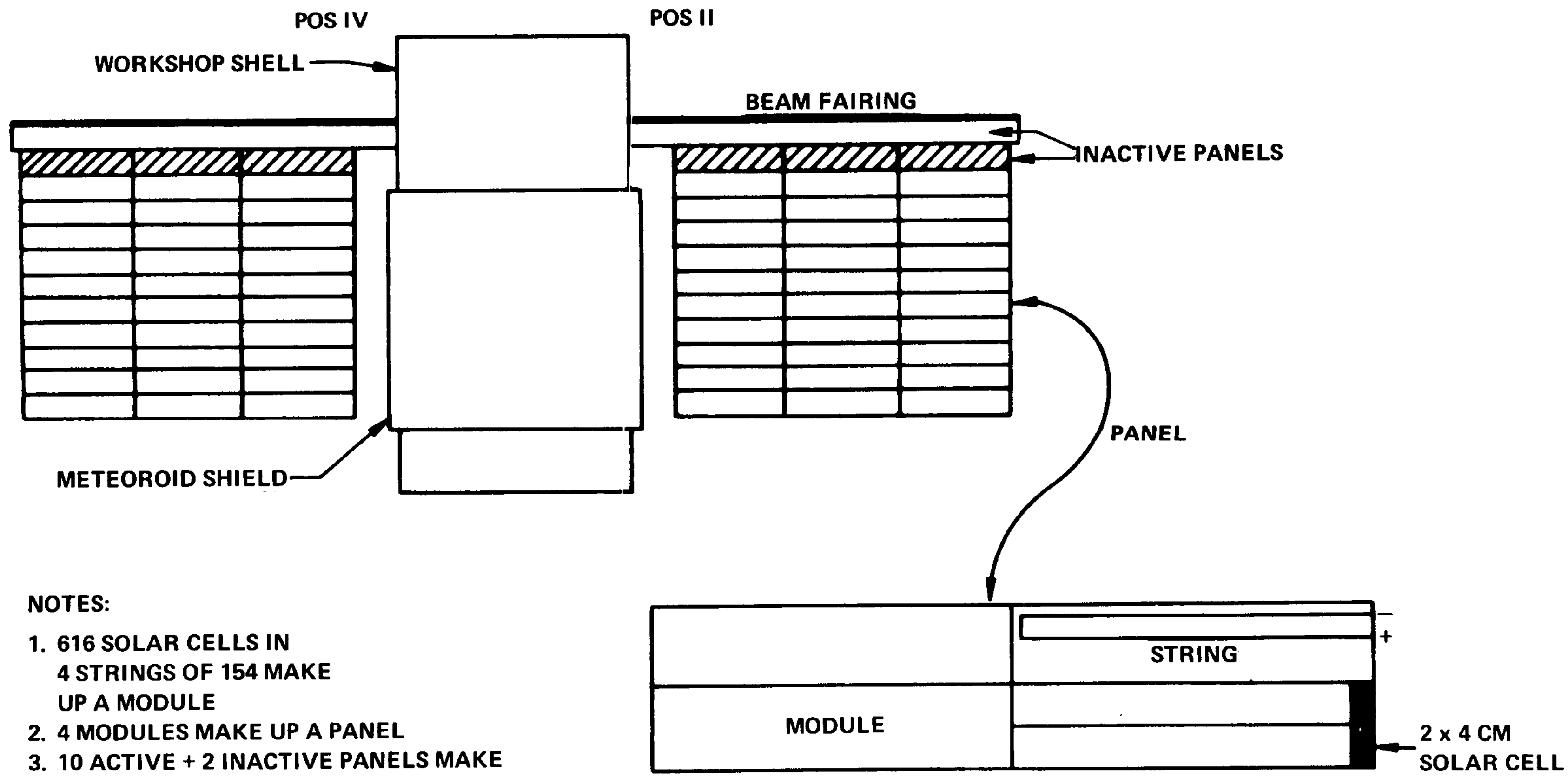
1. F. A. Blake and K. L. Hanson, "The 'Hot Spot' Failure Mode for Solar Arrays," presented at 4th Intersociety Energy Conversion Engineering Conference, Paper No. 699070, Wash., D. C., Sept. 22-26, 1969.

2. TRW Systems Group, "Solar Array System Critical Design Review Data Package", Volume III, Redondo Beach, Calif., Oct. 6-7, 1970.

3. Personal communication with J. L. Miller, MSFC, S&E-ASTR-EPN, Huntsville, Ala., November, 1970.

4. Personal communication with V. Mueller, MDAC-E, St. Louis, Missouri, December, 1970.

5. Centralab Semiconductor Division, Globe Union, Inc., "Solar Engineering Report Number 82", El Monte, Calif., December 19, 1969.



NOTES:

1. 616 SOLAR CELLS IN 4 STRINGS OF 154 MAKE UP A MODULE
2. 4 MODULES MAKE UP A PANEL
3. 10 ACTIVE + 2 INACTIVE PANELS MAKE UP A WING SECTION
4. 3 WING SECTIONS + BEAM FAIRING MAKE UP A WING
5. 2 WINGS MAKE UP SAS

FIGURE 1 - WORKSHOP SOLAR ARRAY SYSTEM GEOMETRY

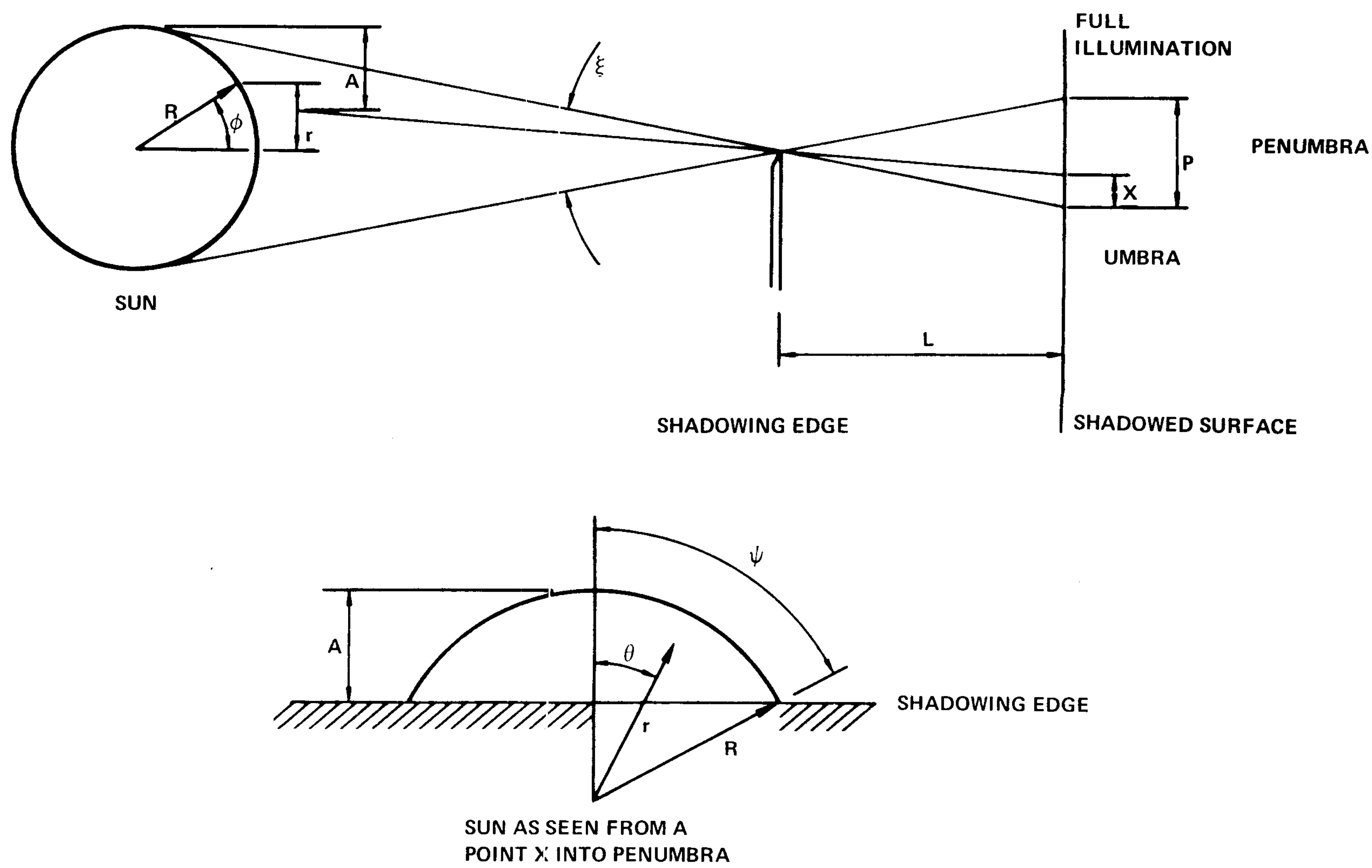


FIGURE 2 - SHADOW GEOMETRY

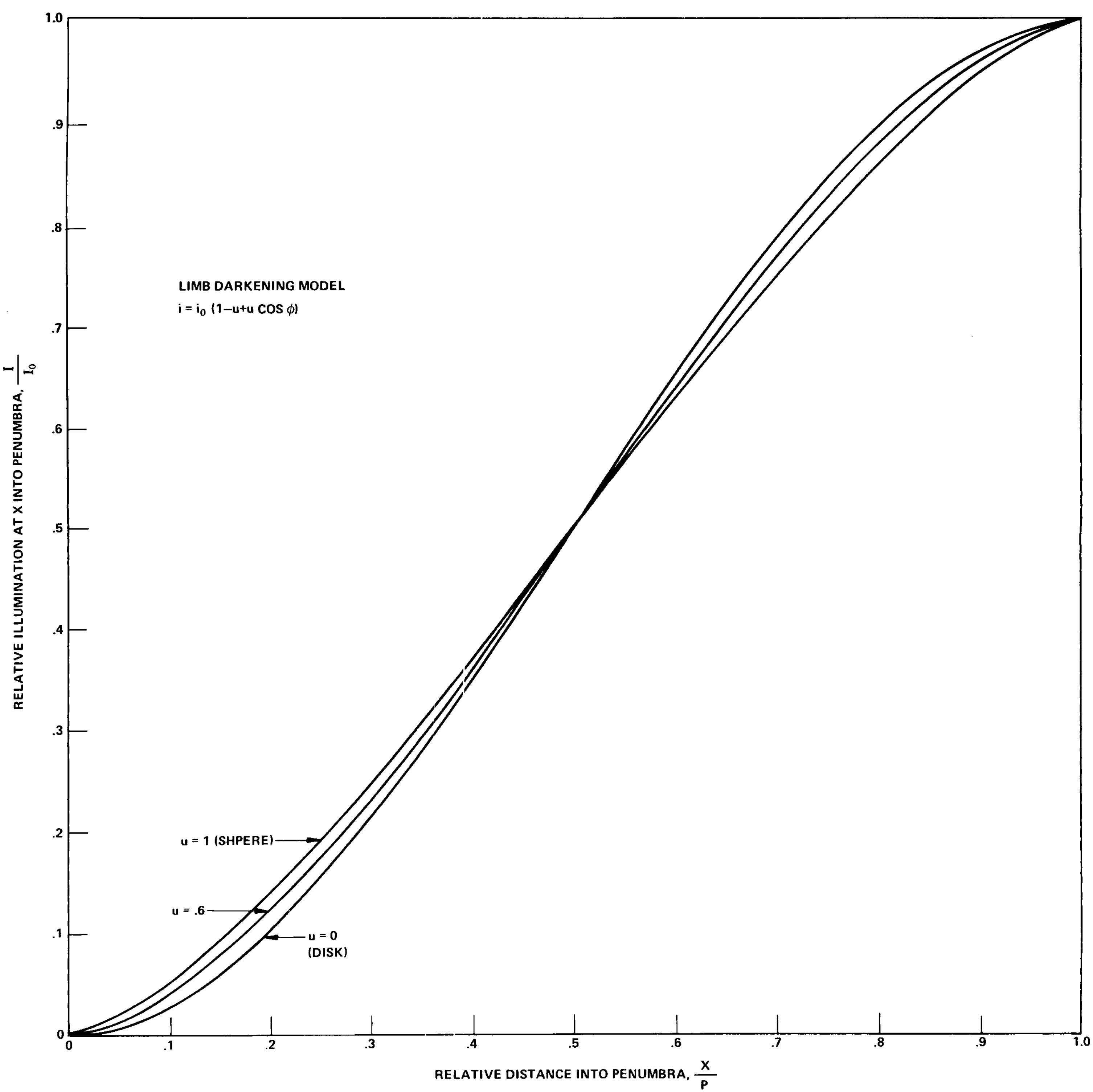


FIGURE 3 - RELATIVE ILLUMINATION THROUGH PENUMBRA

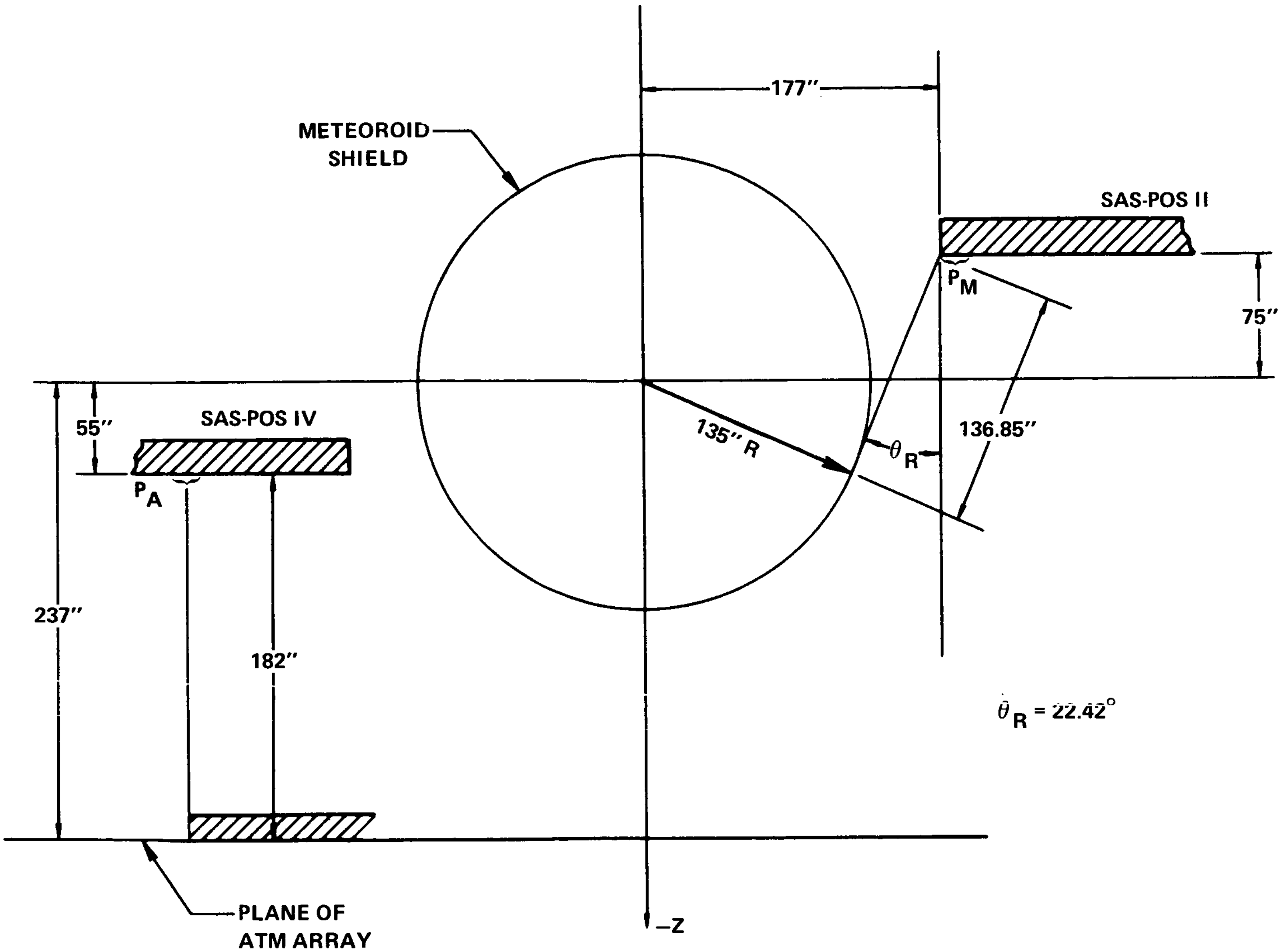


FIGURE 4 - GEOMETRY IN Y-Z PLANE

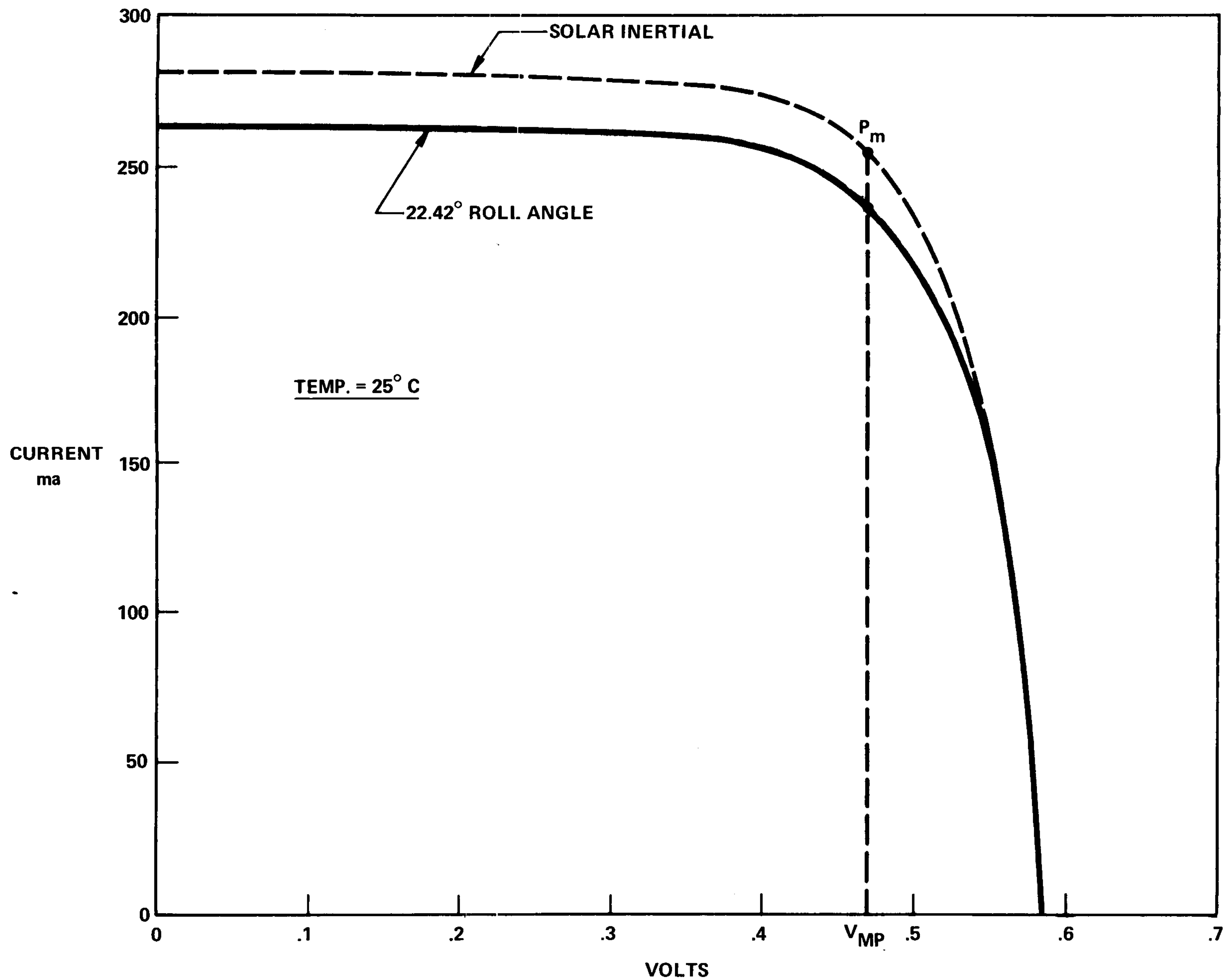


FIGURE 5 - FORWARD CURRENT-VOLTAGE CHARACTERISTIC OF SOLAR CELL OF SAS

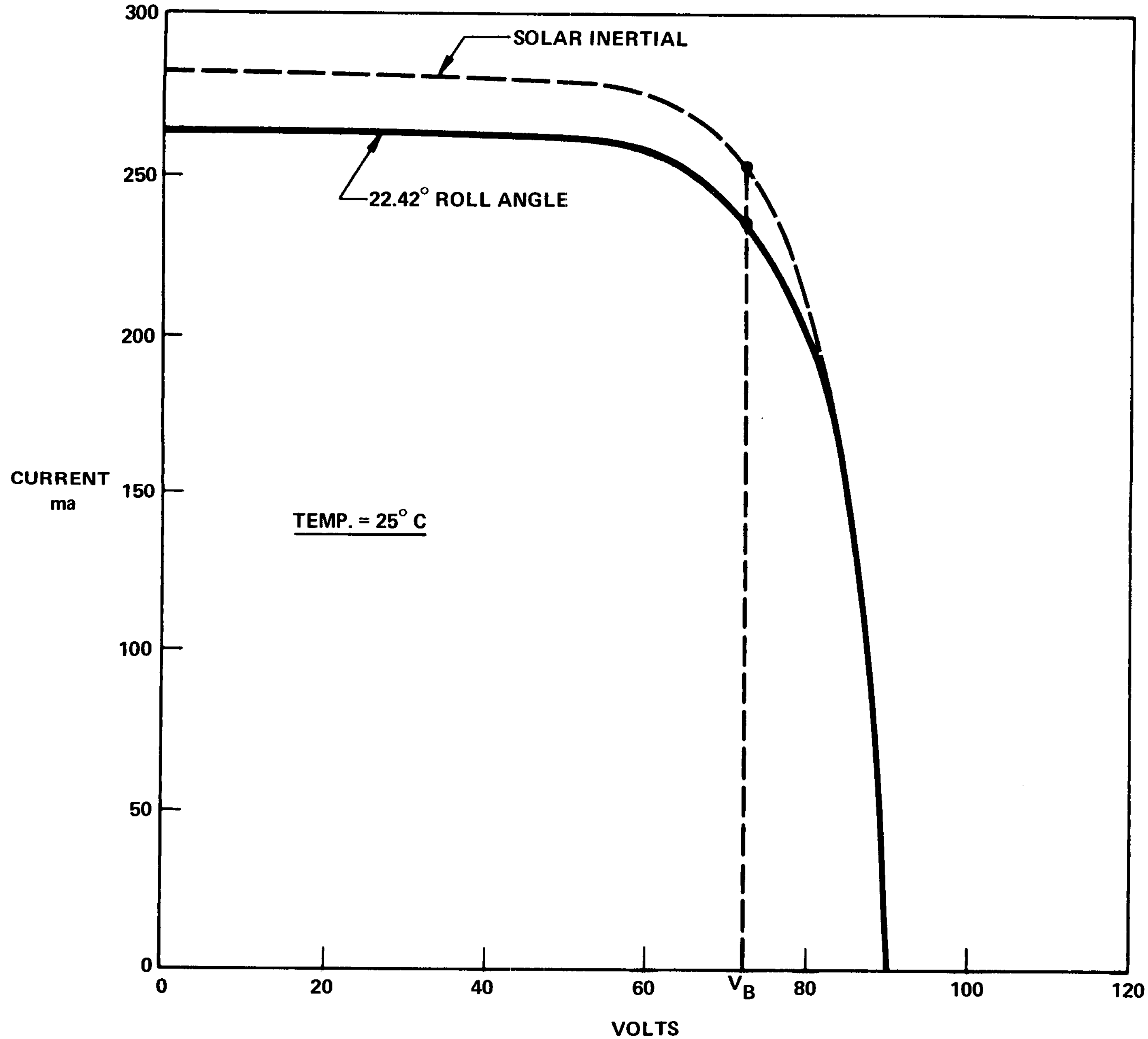


FIGURE 6 - CURRENT-VOLTAGE CHARACTERISTIC FOR A STRING OF 154 CELLS IN SERIES

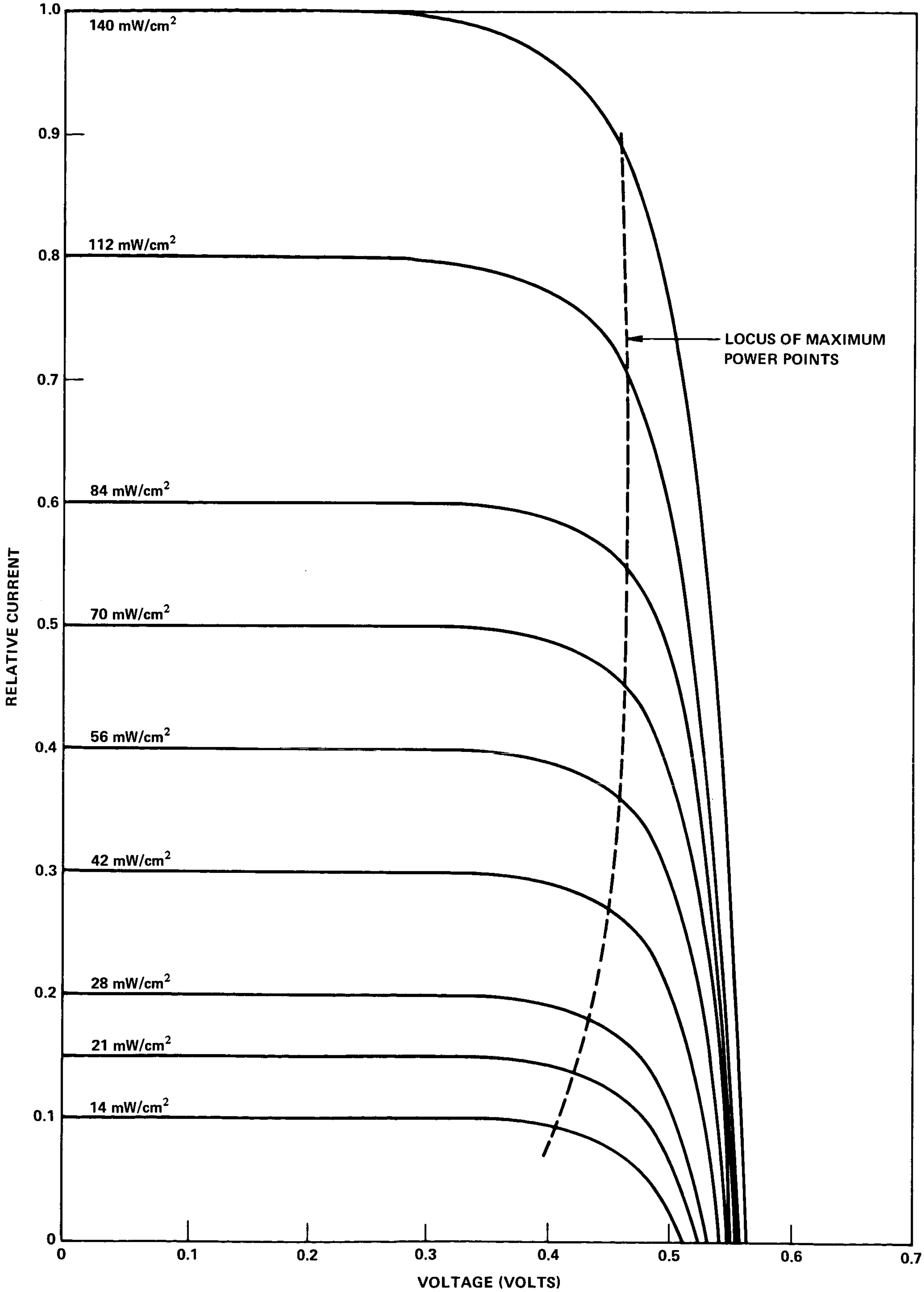


FIGURE 7 - TYPICAL I-V CHARACTERISTICS AS A FUNCTION OF SOLAR IRRADIANCE AT CONSTANT TEMPERATURE

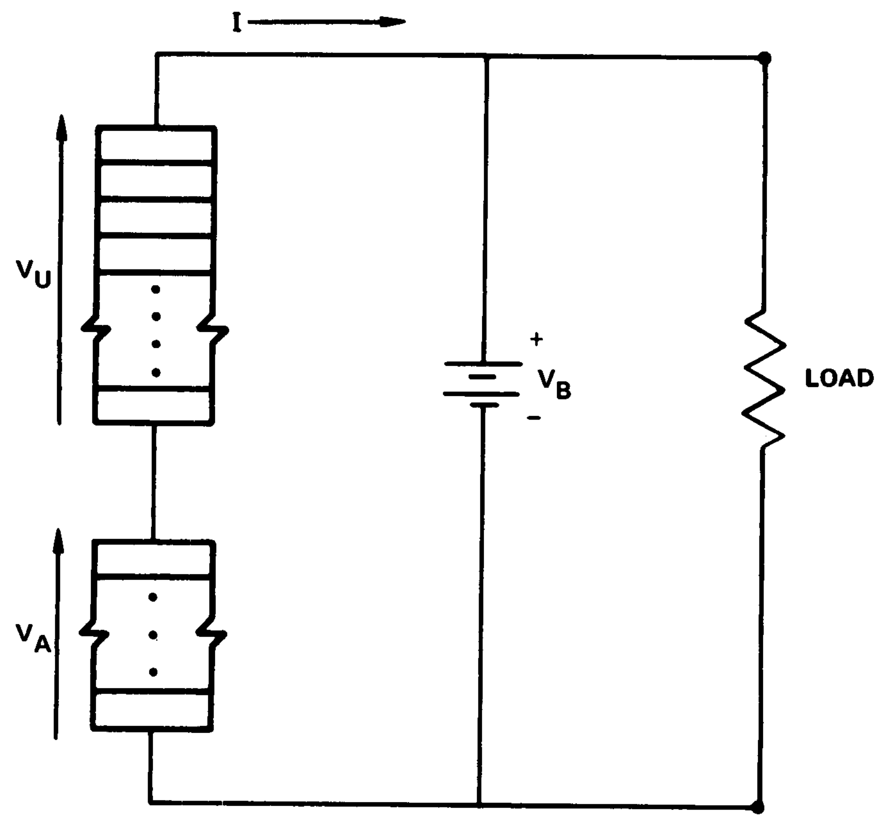


FIGURE 8 - EQUIVALENT CIRCUIT FOR PARTIALLY SHADOWED STRING IN PARALLEL WITH 119 ILLUMINATED STRINGS

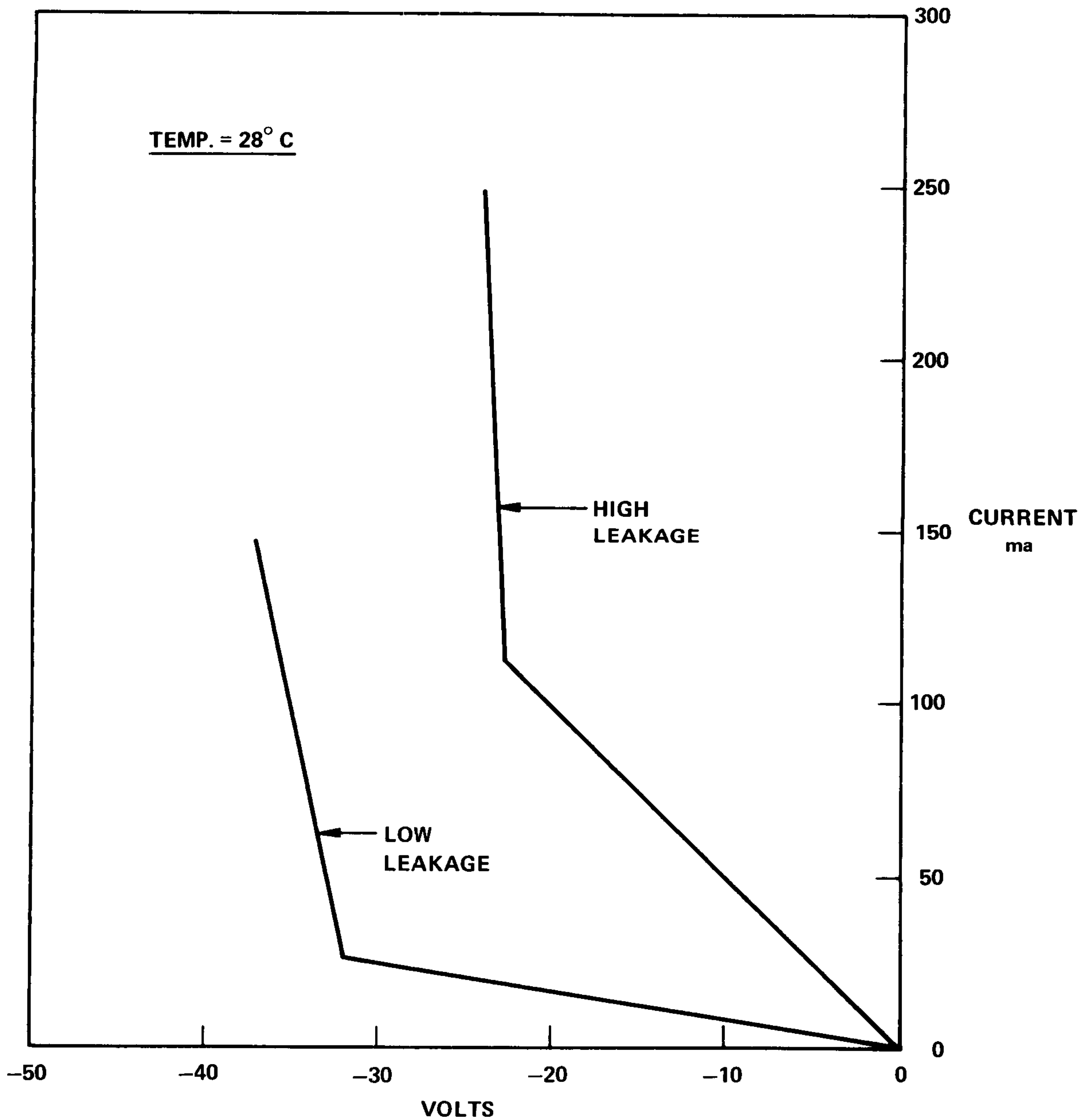


FIGURE 9 - REVERSE VOLTAGE-CURRENT CHARACTERISTIC FOR SAS SOLAR CELLS

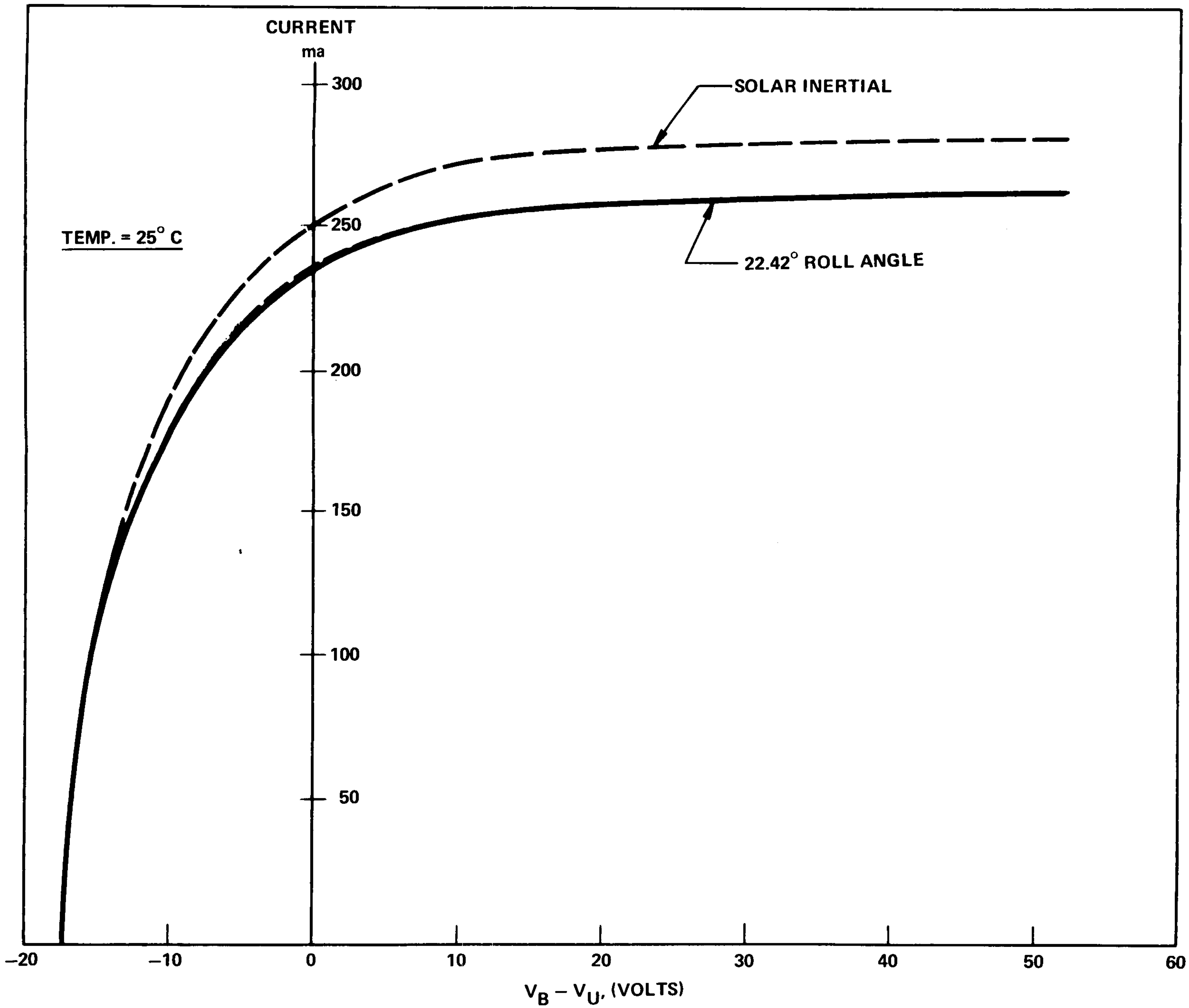


FIGURE 10 - VOLTAGE-CURRENT CHARACTERISTIC IN TERMS OF $V_B - V_U$

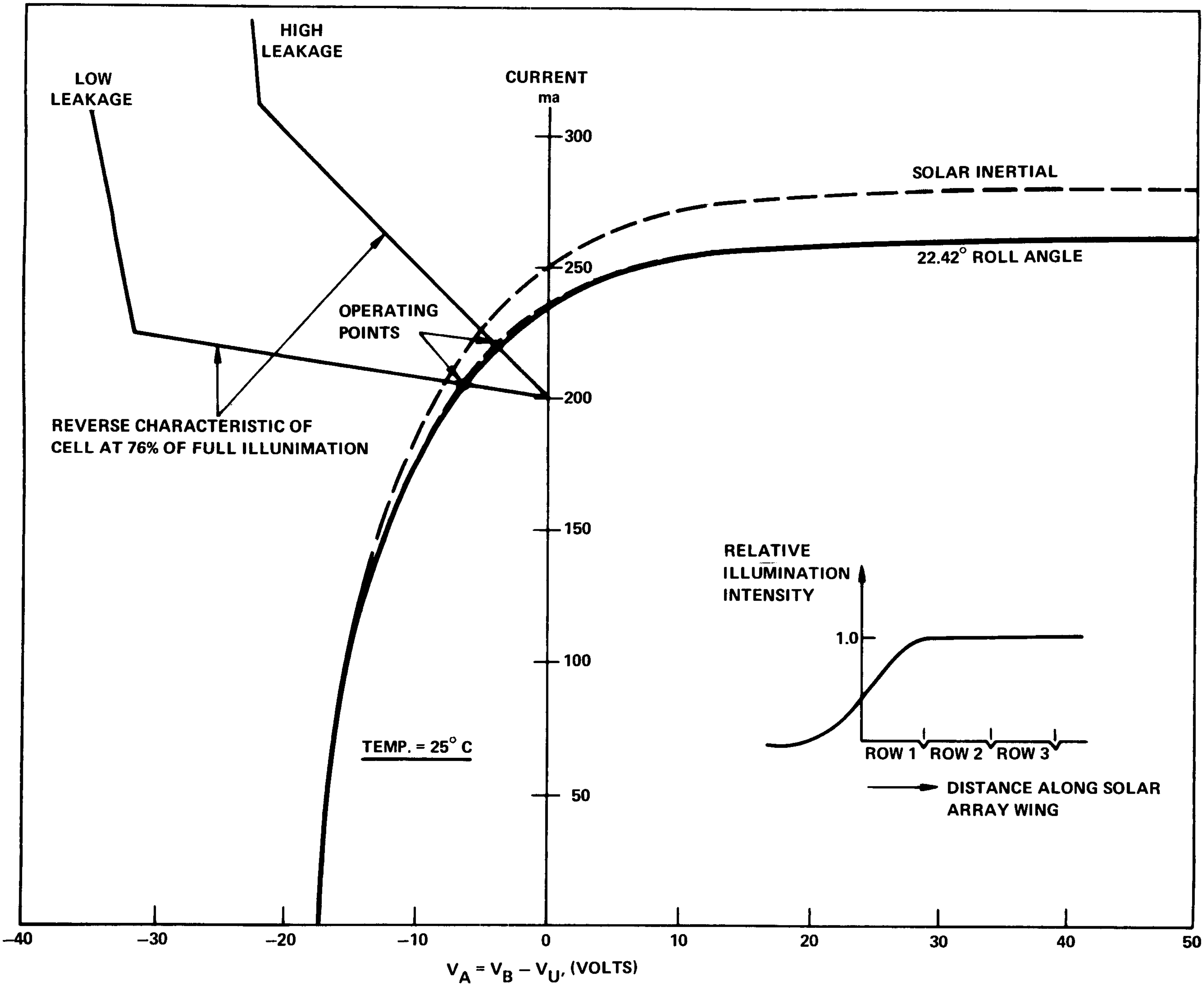


FIGURE 11 - GRAPHICAL DETERMINATION OF OPERATING POINT, ONE CELL PARTIALLY SHADED (.76 I)

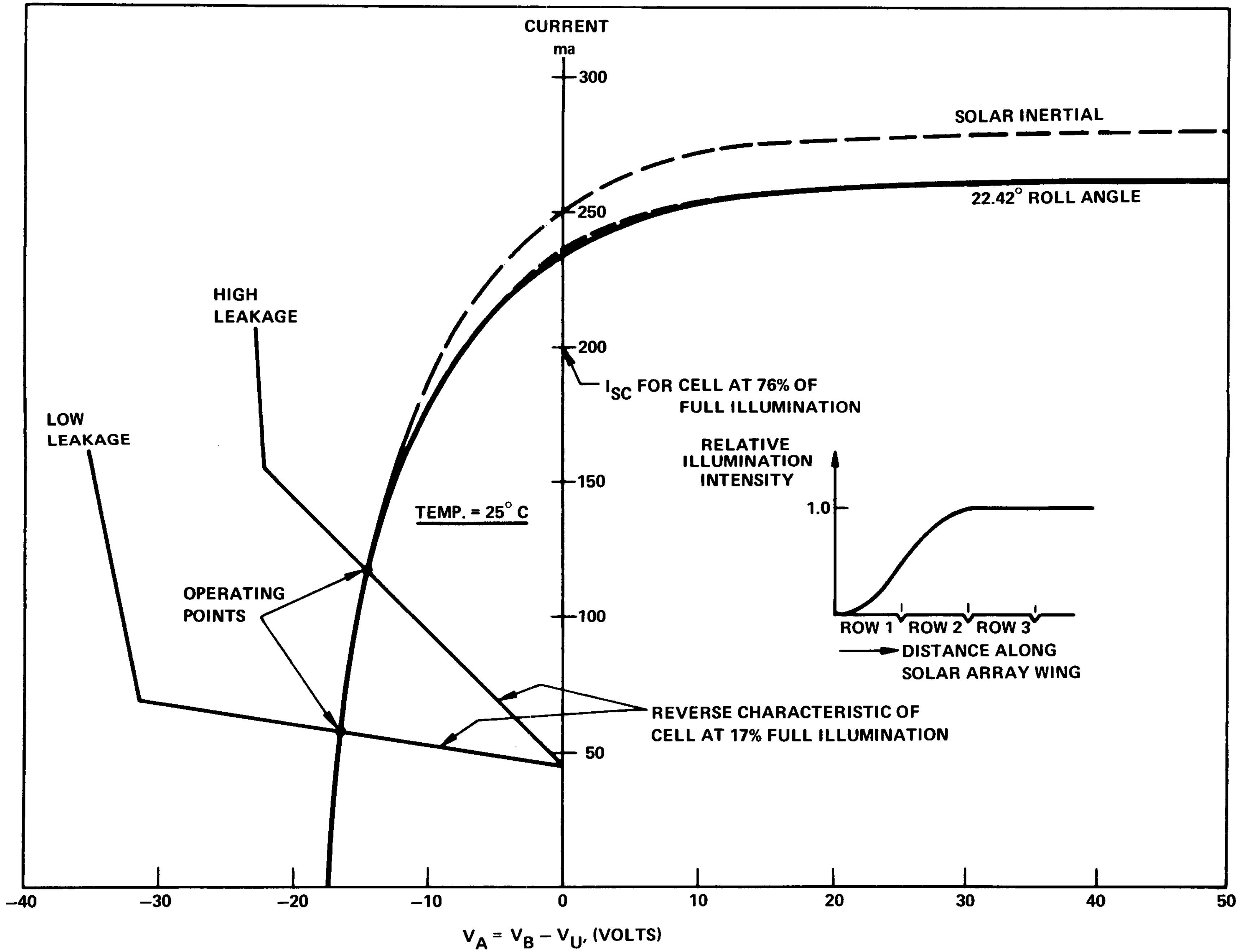


FIGURE 12 - GRAPHICAL DETERMINATION OF OPERATING POINT, TWO PARTIALLY SHADED CELLS (.17 I AND .76 I)

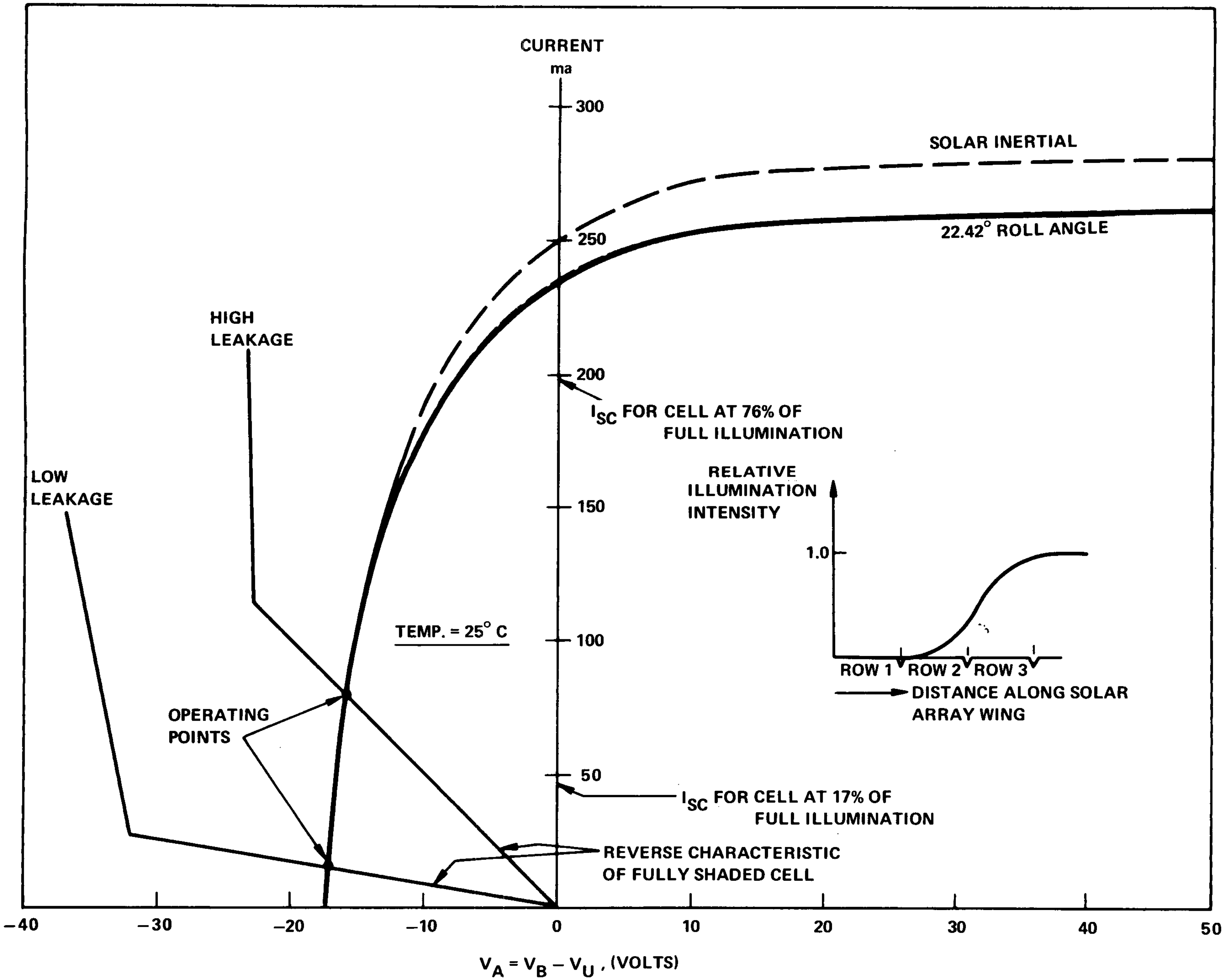


FIGURE 13 - GRAPHICAL DETERMINATION OF OPERATING POINT; ONE FULLY SHADED AND TWO PARTIALLY SHADED CELLS (0.0 I, 0.17 I, AND .76 I)

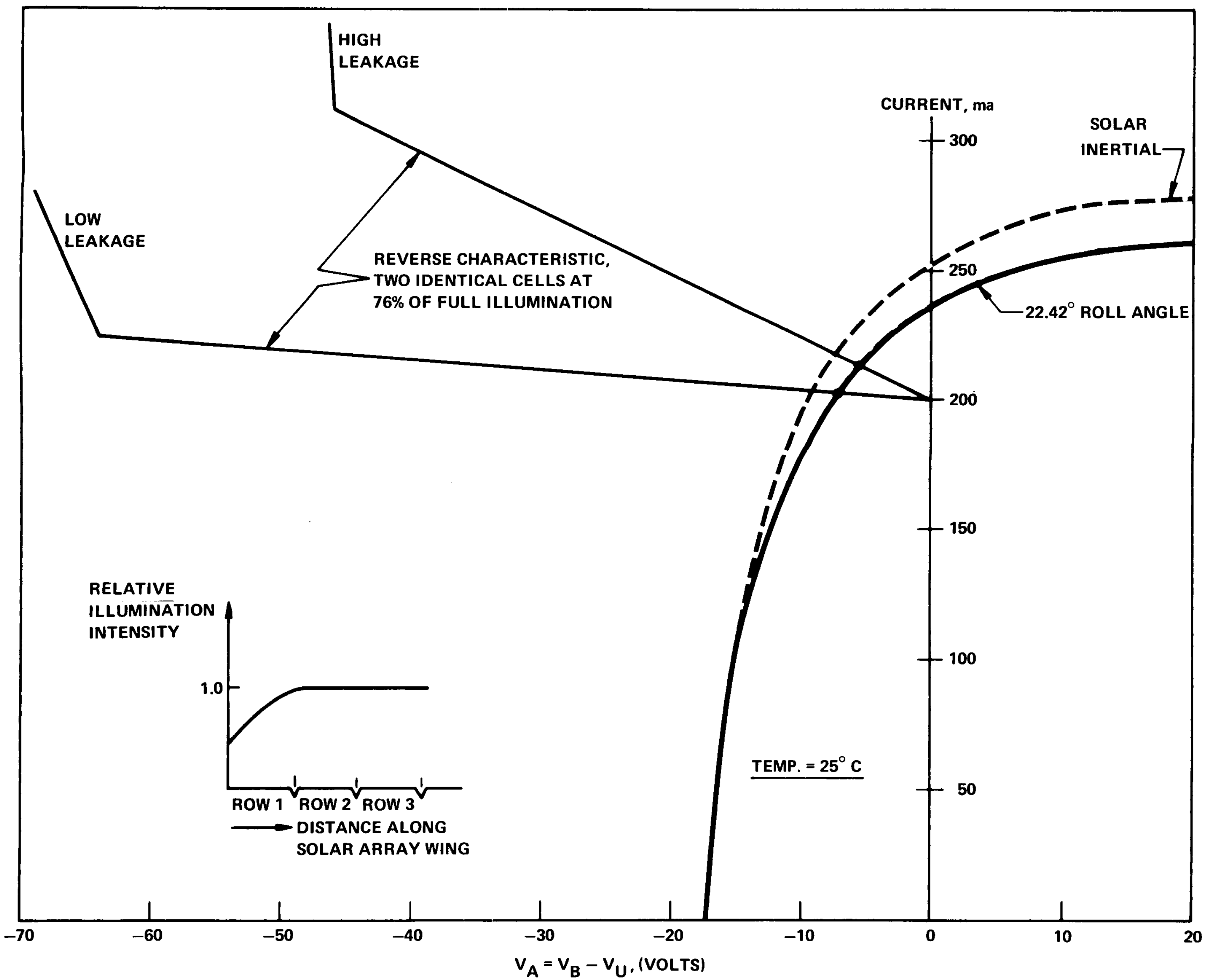


FIGURE 14 - GRAPHICAL DETERMINATION OF OPERATING POINT; TWO PARTIALLY SHADED CELLS (.76I)

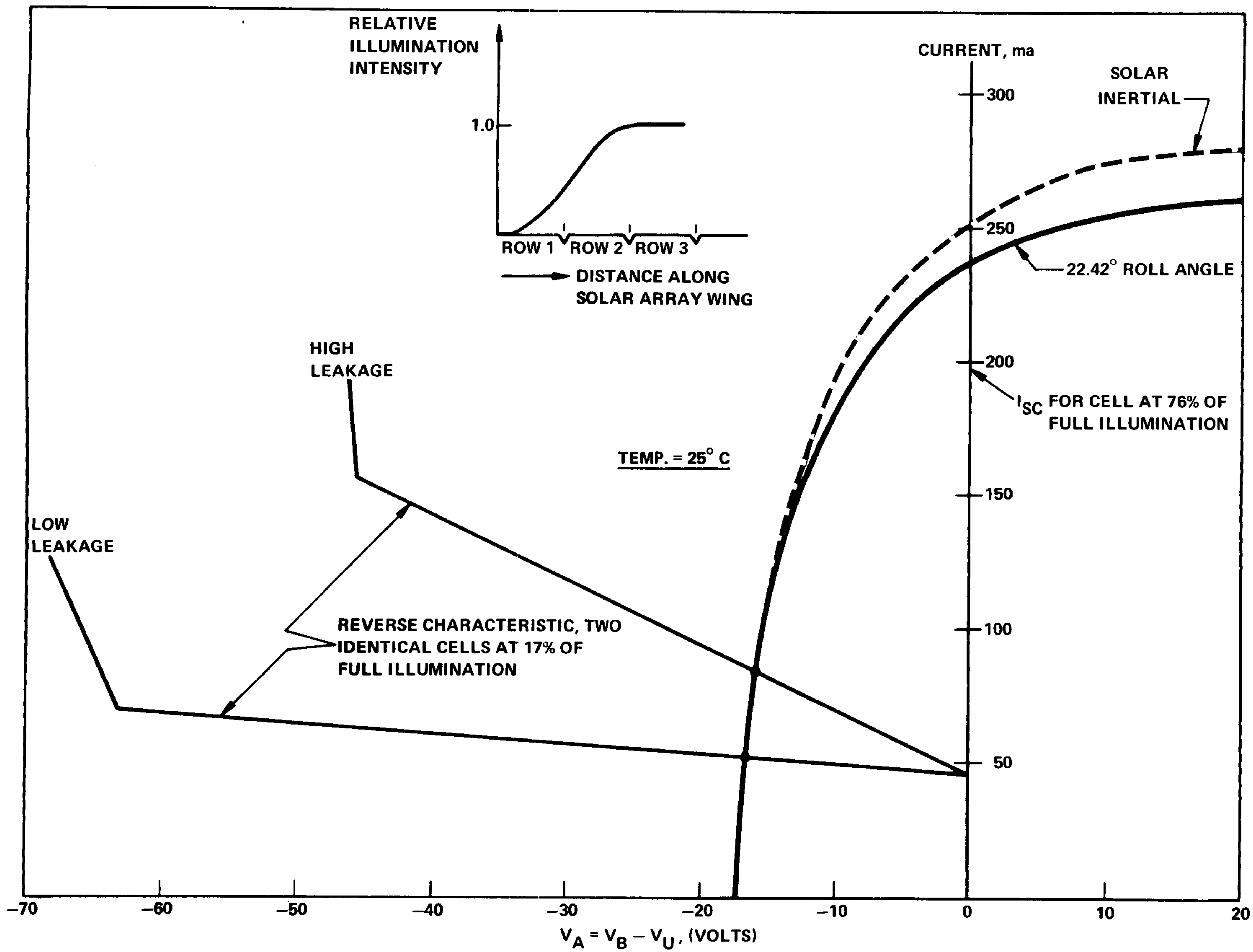


FIGURE 15 - GRAPHICAL DETERMINATION OF OPERATING POINT; FOUR PARTIALLY SHADED CELLS (TWO CELLS AT .76I AND TWO CELLS AT .17I)

BELLCOMM, INC.

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J. J. Sakolosky

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